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**COMPUTATIONAL MODELING
OF
MAGNETICALLY ACTUATED PROPELLANT ORIENTATION**

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INTRODUCTION

Unlike terrestrial applications where gravity positions liquid at the "bottom" of the tank, the location of liquid propellant in spacecraft tanks is uncertain unless specific actions are taken or special features are built into the tank. Some mission events require knowledge of liquid position prior to a particular action: liquid must be positioned over the tank outlet prior to starting the main engines and must be moved away from the tank vent before vapor can be released overboard to reduce pressure. It may also be desirable to positively position liquid to improve propulsion system performance: moving liquid away from the tank walls will dramatically decrease the rate of heat transfer to the propellant, suppressing the boil-off rate, thereby reducing overall mission propellant requirements. The process of moving propellant to a desired position is referred to as propellant orientation or reorientation.

Propulsive reorientation relies on small auxiliary thrusters to accelerate the tank. The inertia of the liquid causes it to collect in the aft-end of the tank if the acceleration is forward. Liquid Acquisition Devices (LAD's) rely on surface tension to hold the liquid within special geometries, (i.e. vanes, wire-mesh channels, start-baskets), to positively position propellants. Both of these technologies add significant weight and complexity to the spacecraft and can be limiting systems for long duration missions. The subject of the present research is an alternate technique for positively positioning liquid within spacecraft propellant tanks: magnetic fields.

LOX is paramagnetic (attracted toward a magnet) and LH2 is diamagnetic (repelled from a magnet). Order-of-magnitude analyses, performed in the 1960's to determine required magnet size, concluded that the magnets would be prohibitively massive and this option has remained dormant during the intervening years. Recent advances in high-temperature superconducting materials hold the promise of electromagnets with sufficient performance to support cryogenic propellant management tasks. In late 1992, NASA MSFC began a new investigation in this technology commencing with the design of the Magnetically-Actuated Propellant Orientation (MAPO) experiment. A mixture of ferrofluid and water is used to simulate the paramagnetic properties of LOX and the experiment is being flown on the KC-135 aircraft to provide a reduced gravity environment. The influence of a 0.4 Tesla ring magnet on flow into and out of a subscale Plexiglas tank is being recorded on video tape.

The most efficient approach to evaluating the feasibility of MAPO is to compliment the experimental program with development of a computational tool to model the process of interest. The goal of the present research is to develop such a tool. Once confidence in its fidelity is established by comparison to data from the MAPO experiment, it can be used to assist in the design of future experiments and to study the parameter space of the process. Ultimately, it is hoped that the computational model can serve as a design tool for full-scale spacecraft applications.

MATHEMATICAL MODEL

Although the practitioner of experimental or computational fluid mechanics may have familiarity with many of the features of the research problem, it is less likely that he/she will have a strong background in the magnetic and paramagnetic aspects of the problem. The author spent considerable time and effort retrieving the background information in these areas and has

collected the basic information into a single resource that it is hoped will be of value to other researchers who tackle this problem, "Magnetism and the Flow of Paramagnetic Fluids: An Introduction for the Non-Specialist." In addition to this review of the basic physics, 22 papers related to the flow of paramagnetic fluids and ferrofluids were extracted from the literature and assembled into a reference resource.

LOX and LH2 are reasonably well represented as incompressible, constant property, Newtonian fluids and therefore the flow of interest can be modeled using a modified form of the Navier-Stokes equations

$$\rho \frac{\partial \bar{V}}{\partial t} + \rho (\bar{V} \cdot \nabla) \bar{V} = -\nabla p + \mu \nabla^2 \bar{V} + \rho \bar{g} + \mu_0 \chi H \nabla H$$

where ρ , \bar{V} , p , μ , and \bar{g} have the usual definitions of density, velocity, viscosity, and gravity, μ_0 is the permeability of free space, \bar{H} is the magnetic intensity, \bar{M} is the magnetization, and χ is the susceptibility. The last term on the right-hand side is known as the Pondermotive force and provides the coupling between the magnetic field and the fluid motion. The form shown assumes that: the direction of the magnetization vector is always in the direction of the local magnetic field, the fluid is electrically nonconducting, the displacement current is negligible, and the magnetization is linear. In addition to the usual flow boundary conditions, the normal stress boundary condition at a gas/liquid interface is given by:

$$\Delta p = \sigma \kappa + \frac{1}{2} \mu_0 \left[(\bar{M} \cdot \hat{n})_{\text{liq}}^2 - (\bar{M} \cdot \hat{n})_{\text{gas}}^2 \right]$$

where the first term is the "pressure jump" at the interface due to surface tension and the second term is the "magnetic pressure" due to the change in magnetization across the interface.

COMPUTATIONAL MODEL

A computational tool for the simulation of MAPO must be able to solve all of equations and boundary conditions identified above and must model the large interface deformation and mass transport associated with bulk propellant motion within the spacecraft tank. These requirements eliminate most candidate CFD codes and identify the RIPPLE code as uniquely well qualified to serve as the foundation for building the desired computational tool. RIPPLE was developed at the Los Alamos National Laboratory under an interagency agreement with NASA and source code is readily available. Except for the Pondermotive force term, the baseline code provides all of the required capabilities and the fidelity of this code in modeling propulsive propellant reorientation has been previously demonstrated.

RIPPLE models the transient laminar flow of an incompressible Newtonian fluid. The flow field is discretized into finite volumes to form a nonuniform computational mesh. A staggered-grid approximation to the continuity and momentum equations produces a nonlinear system of algebraic equations that is solved using a two-step projection method. The VOF technique is used to follow the advection of mass through an Eulerian mesh. The Continuum Surface Force (CSF) model provides a sophisticated and robust model for surface tension forces. A supporting graphics package, known as RGO, was ported to a workstation (SGI 4D/35TG) in the MSFC computational environment. The analysis code contains a sequence of subroutine

calls in which each subroutine computes the contribution of a force term to momentum equation. A new subroutine, ponder, has been written to compute the contribution of the Pondermotive force and this subroutine has been inserted into the calling sequence. Additional modifications to support the magnetic model have been accomplished including changes to the I/O subroutines, common blocks, and modification of RGO to support variables introduced by the magnetic model.

TEST CASES

Space limitations require that only a few selected computational results be presented in this report. One set of test cases were constructed with magnetic fields corresponding to; $dh/dx = \text{constant}$, $dh/dy = \text{constant}$, and $dh/dx = dh/dy = \text{constant}$. Figure 1 shows that, as required by the theory, constant pressure contours are straight lines orthogonal to the gradient of the magnetic field, (the small deflections near the walls are an anomaly of the graphics). Figure 2 shows the predictions of a test case designed to demonstrate the modified code's ability to simulate a flow, driven by the pondermotive force, with a highly deforming free surface and surface tension. An imposed magnetic field gradient in the horizontal direction produces a region of high pressure at the left edge of the cavity which drives the bubble toward the right wall. Many other test cases have been studied and excellent results were obtained for all.

The goal of this effort, modeling the MAPO experiment has proven to be the most difficult test of the code. A dipole positioned along the tank centerline just below the bottom of the tank is used to represent the magnet. During simulation, a strong vortex quickly formed around the centerline at the bottom of the tank producing a geyser along the tank centerline that is not credible. A major effort ensued to determine the cause of the vortex. The pressure contours appeared credible. A variety of variations in modeling assumptions were studied to no avail. The expressions for magnetic field intensity and its gradient were re-derived and their numerical implementation checked for correctness using three different formulations. No errors were found. Analytical evaluation of the expression for the body force induced by the dipole field verified that the force field is irrotational. After considerable detective work, it was concluded that the source of vorticity might be the finite-difference approximations used to represent the body force in the code. A numerical experiment was performed to compare the curl of the body force computed small perturbations about the location where the force is computed to the curl computed "as the computational model would see it." The results were conclusive and supported the hypothesis: the curl was being artificially generated in the code because the strong and highly nonlinear magnetic field in the neighborhood the dipole was not being adequately represented. The final analysis of the summer simulated the MAPO experiment using a mesh that is "packed" toward the region of high field strength near the dipole. The case starts with a flat free surface located at the mid-height of the tank and the gravitational field is linearly reduced from 1 g to 0.01 g during the first seven seconds to simulate the KC 135 environment. Figure 3 presents a sequence of flow fields predicted for elapsed times from problem start of 2.0, 4.0, 6.0, 10.0, and 20.0 seconds. Although this result is now credible, further testing must be performed before confidence in the quality of the flow field predictions can be established.

FUTURE DIRECTIONS

The preceding text describes twenty weeks, (two summers), of effort. A fairly difficult problem has been approached and preliminary tests indicate a good chance of success for the methods and tools developed. The next step should be an effort to improve the accuracy of the pondermotive force model. Although mesh refinement definitely helped reduce the problem of numerical vorticity, the study shows that elimination of this artifact may impose an unacceptable computational burden on other cases. Once this is accomplished, the code should be exercised on additional test cases that have been identified during the literature search for which experimental data or analytical solutions are available. The fidelity of the code should then be evaluated by comparing computational predictions to measurements from the MAPO experiment. Successful completion of this research program will produce a valuable tool that can be used for the design of additional experiments, to study the parameter space of the MAPO process, and ultimately as a design tool for full-scale spacecraft applications.

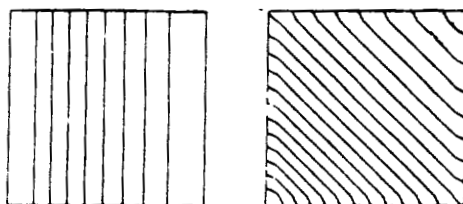


Figure 1

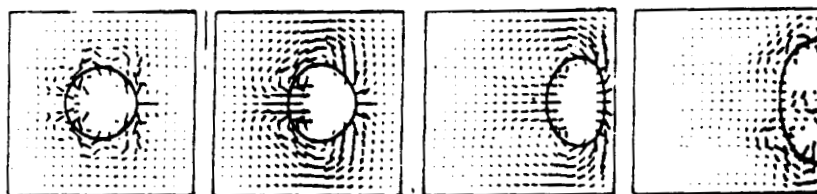


Figure 2

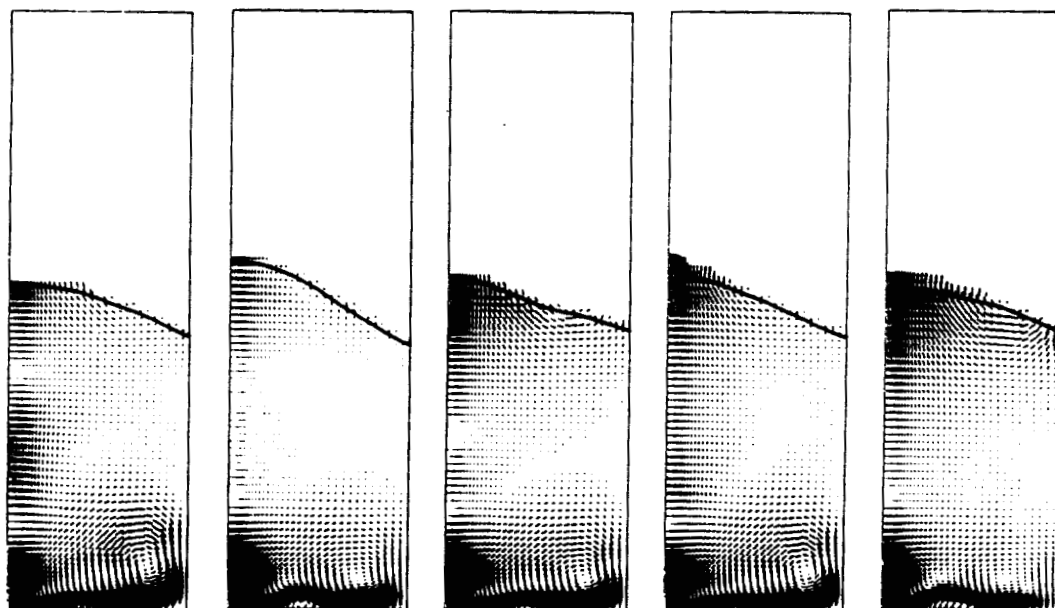


Figure 3